

Hadron Production at RHIC

- A few applications -

Kazutaka Sudoh (KEK)
RHIC Spin Fest
29 July 2005



I. Introduction

II. Neutral π^0 Production

$$\vec{p} + \vec{p} \rightarrow \pi^0 + X$$

III. Charged π^\pm Production

$$\vec{p} + \vec{p} \rightarrow \pi^+ / \pi^- + X$$

IV. Charm-Associated W^\pm Production

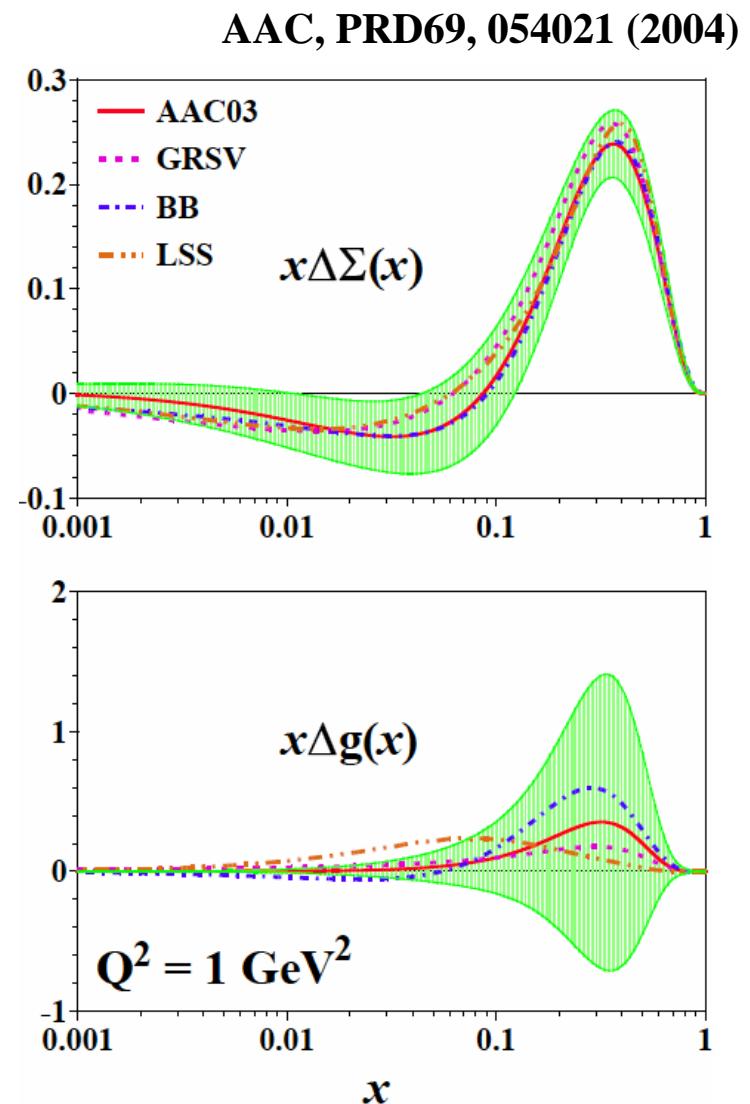
V. Summary

$$p + \vec{p} \rightarrow W^\pm + c / \bar{c} + X$$

I. Introduction

Spin Content: $\Delta\Sigma, \Delta G$

- **1st stage – polarized DIS**
 - Extraction of $\Sigma\Delta q_i$
 - $\Delta u_\nu, \Delta d_\nu$: well determined
 - Flavor blind
 - $\Delta\Sigma \sim 0.1-0.3$
- **2nd stage – RHIC, semi-inclusive DIS**
 - Extraction of $\Delta g, \Delta s$
 - Flavor structure of Δq^{bar}
 - $\Delta G \sim 0.5 \pm 1.2$





RHIC experiments

- Δg
- ★ – Prompt photon production
 - qg process dominates, no FF ambiguity, low statistics
 - Heavy flavor production
 - gg process dominates
 - Pion production
 - High statistics, many sub-processes
 - ⋮
- $\Delta \bar{q}$
- ★ – W^\pm production: $\Delta \bar{u}, \Delta \bar{d}$
 - Charm-Associated W^\pm production: $\Delta s, \Delta \bar{s}$
 - Flavor decomposition



- **200 GeV Run**

- Neutral π^0 Production

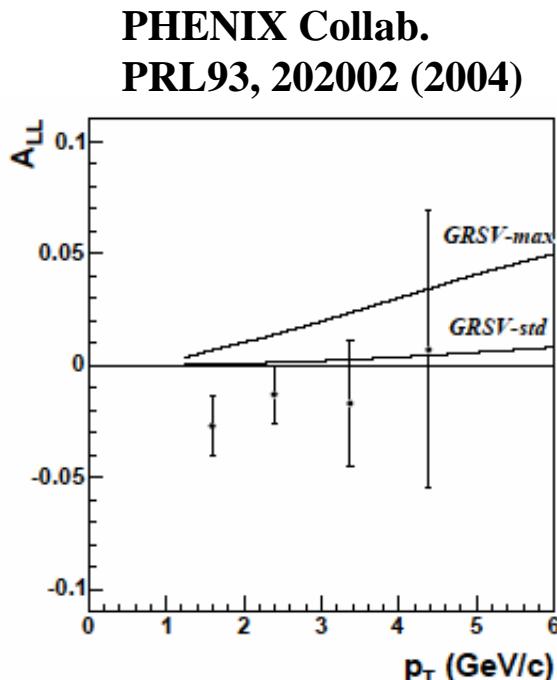
$$\vec{p} + \vec{p} \rightarrow \pi^0 + X$$

- Charged π^\pm Production

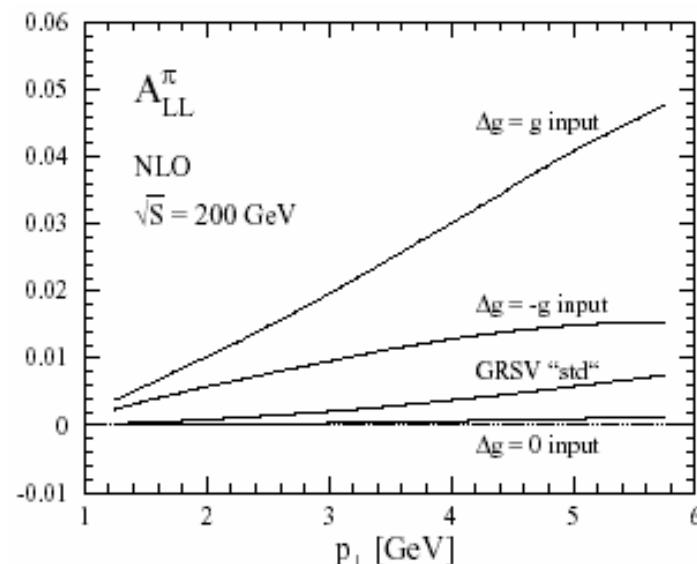
$$\vec{p} + \vec{p} \rightarrow \pi^+ / \pi^- + X$$

II. Negative Asymmetry

- Comparison $A_{LL}^{\pi^0}$ with the PHENIX data
 $\sqrt{s} = 200 \text{ GeV}, |\eta| \leq 0.35$
- pQCD prediction indicates positive asymmetry.



B. Jagar *et al.*,
PRL92, 121803 (2004)



Upper bound
 $\Delta g = g$

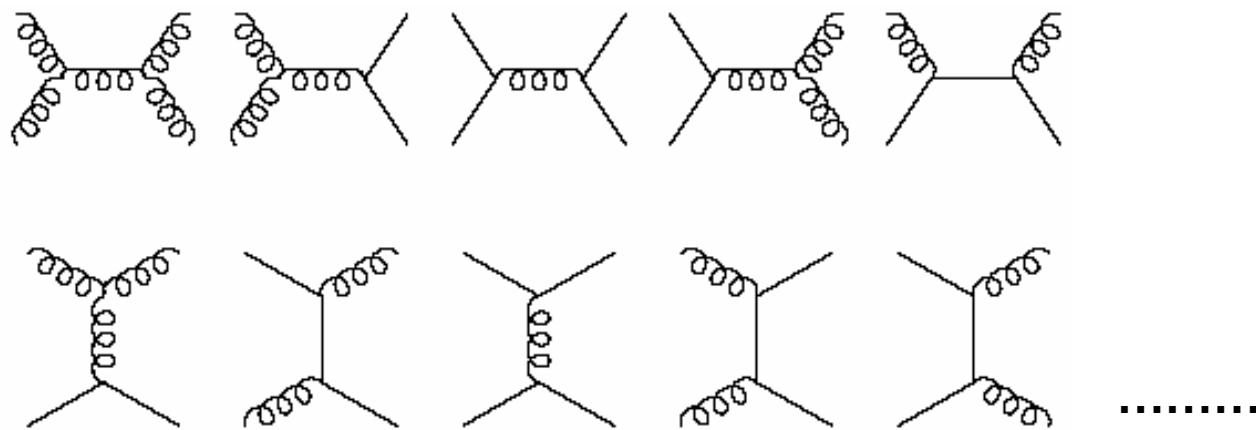
If $\Delta g(x)=0$ at initial scale,
 $\Delta g(x)$ has finite value through Q^2 evolution.

Inclusive π^0 Production @RHIC

- **Subprocesses for π^0 production**

- $O(\alpha_s^2)$ 2 2 tree-level channels in LO

$$gg \rightarrow q(g)X, \quad qg \rightarrow q(g)X, \quad qq \rightarrow qX,$$
$$q\bar{q} \rightarrow q(g,q')X, \quad qq' \rightarrow qX, \quad q\bar{q}' \rightarrow qX$$

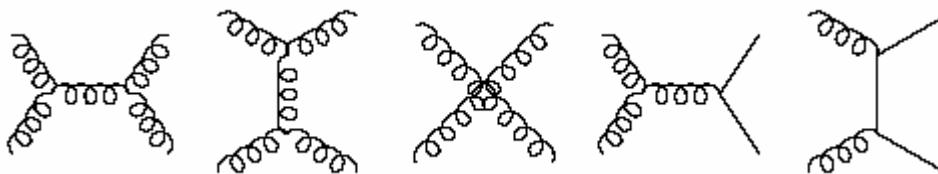


well-defined in perturbation theory in s

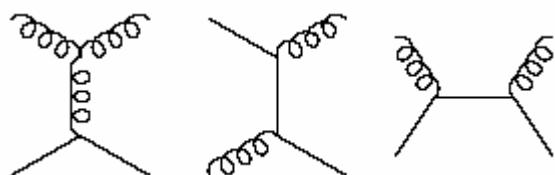
Inclusive π^0 Production @RHIC

- **Dominant contribution:**

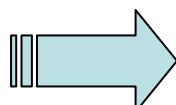
$gg \rightarrow q(g)X$: in small p_T



$qg \rightarrow q(g)X$: in large p_T



- **π^0 spin asymmetry is sensitive to $\Delta g(x)$.**



Determined by a balance between
 gg and qg contributions.

Double Spin Asymmetry

Longitudinal Double Spin Asymmetry:

$$A_{LL}^{\pi^0} \equiv \frac{[d\sigma_{++} - d\sigma_{+-}]/dp_T}{[d\sigma_{++} + d\sigma_{+-}]/dp_T} = \frac{d\Delta\sigma/dp_T}{d\sigma/dp_T}$$

$$\frac{d\Delta\sigma}{dp_T} \equiv \frac{1}{2} \left[\frac{d\sigma_{++}}{dp_T} - \frac{d\sigma_{+-}}{dp_T} \right] : |\eta| \leq 0.35, \quad Q^2 = p_T^2$$

$$= \sum_{a,b,c} \int d\eta \int dx_a \int dx_b \int dz \quad \frac{\Delta f_a(x_a, Q^2) \Delta f_b(x_b, Q^2)}{dp_T d\eta} \frac{d\Delta\hat{\sigma}}{dp_T d\eta} D_c^\pi(z, Q^2)$$

PDF and FF:
Determined using
experimental data

Amplitude:
Calculable in pQCD

Where does the inconsistency come from?

Where does ambiguity come from?

- **Fragmentation function: $D^\pi(z)$**

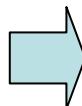
- Unpolarized π^0 cross section by the PHENIX is consistent with pQCD calculation.

$$\sqrt{s} = 200 \text{ GeV}, \quad |\eta| \leq 0.35$$

- Determined from e^+e^- data

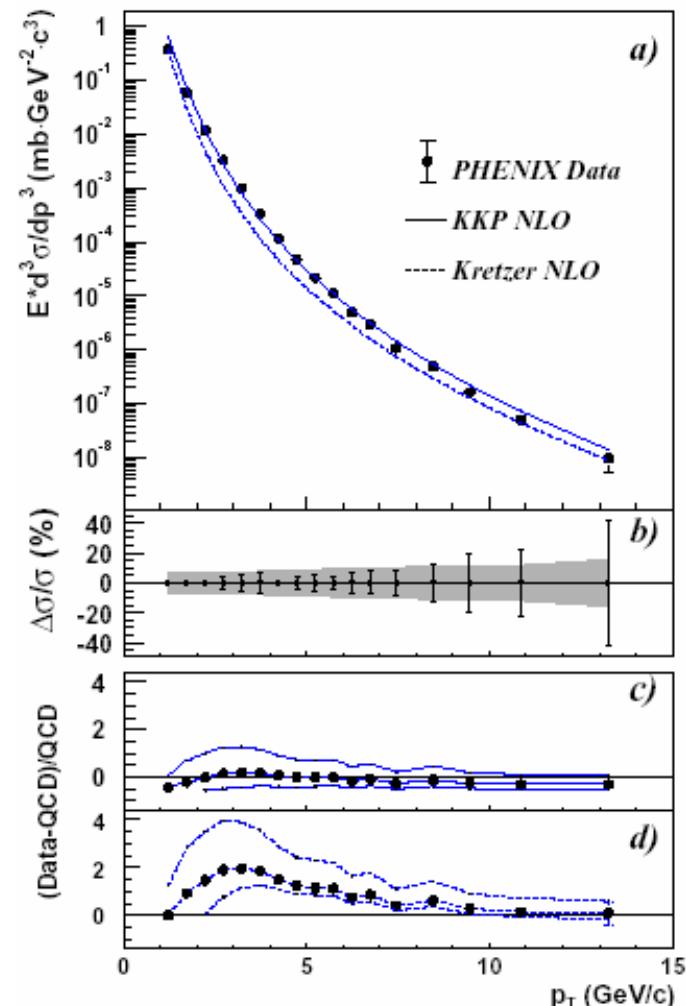
- **Pol. quark distribution: $\Delta q(x)$**

- Flavor blind reaction
- Depends on the sum $\Delta q(x) + \Delta \bar{q}(x)$.



Ambiguity comes from $\Delta g(x)$

PHENIX Collab. PRL91, 241803 (2003)

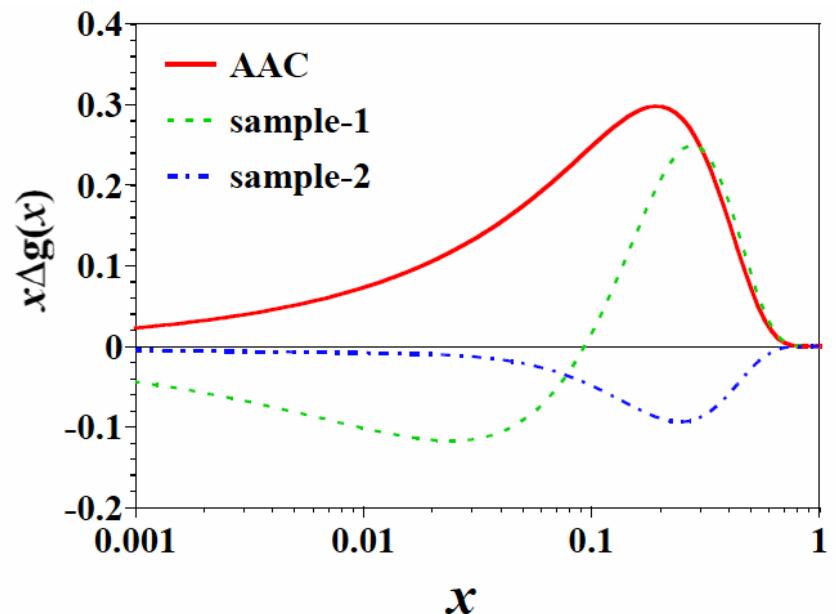


Modification of $\Delta g(x)$

Can we obtain negative asymmetry by modifying $\Delta g(x)$?

3 configurations of $\Delta g(x)$ within their uncertainty

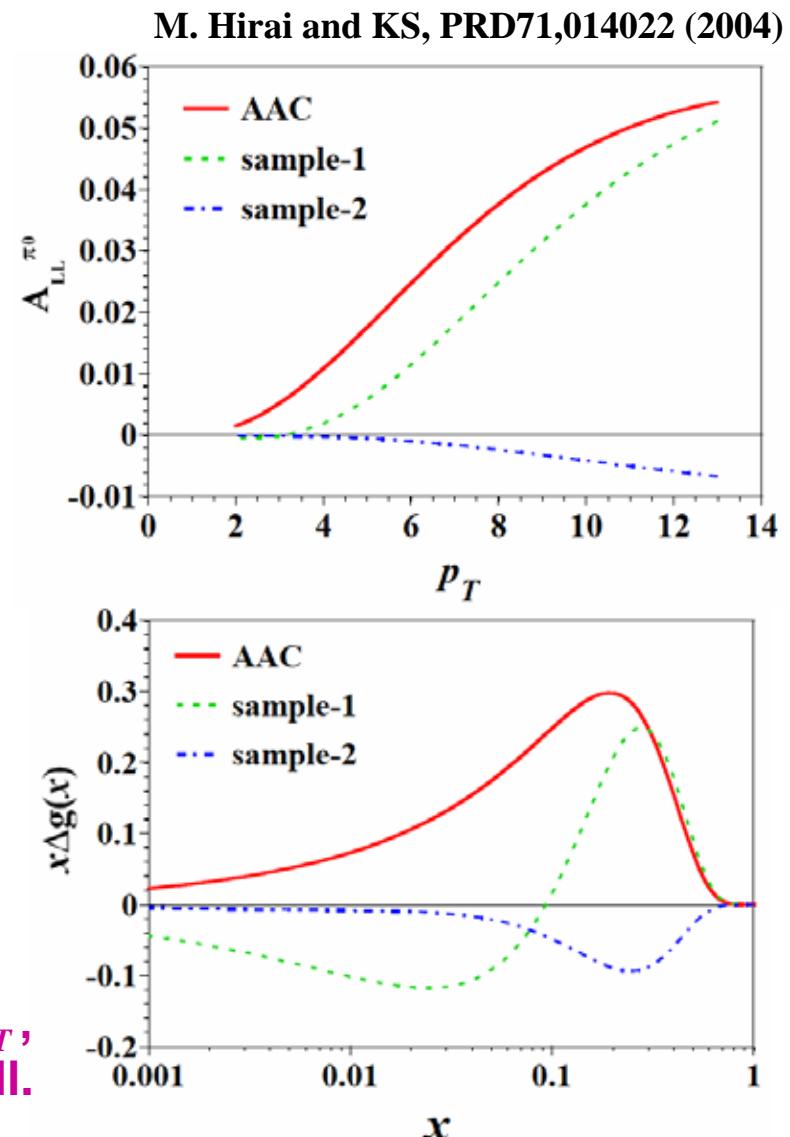
- **Scen.1 standard Δg**
 - global analysis with pol. DIS
 - A_{LL} does not become negative.
- **Scen.2 Δg with a node**
 - possibility $gg < 0$ ($\Delta g(x_a) \cdot \Delta g(x_b) < 0$)
 - $|x_a - x_b|$ is small in $\eta < 0.38$
- **Scen.3 negative Δg**
 - $gg > 0, qg < 0$
 - $|\Delta g(x)|$ is small in low x
 - $|\Delta g(x)|$ is large in high x



$\Delta g(x)$ has Q^2 dependence by DGLAP equation.

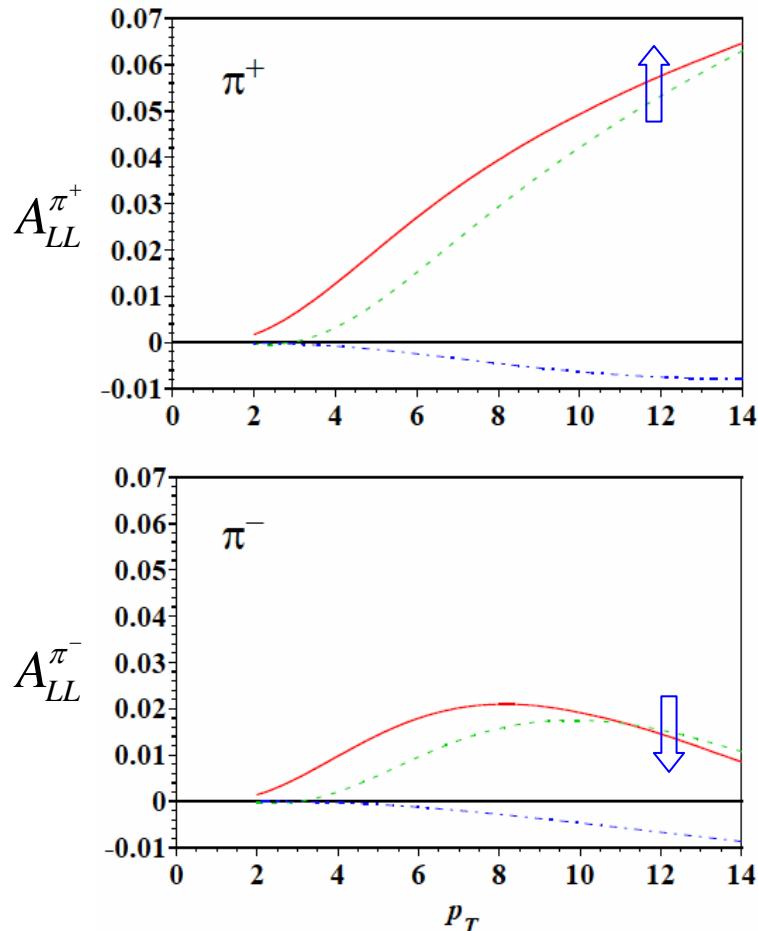
$A_{LL}^{\pi^0}$ with modified $\Delta g(x)$

- **AAC $\Delta g(x)$**
 - Both gg and $qg > 0$
 - A_{LL} is positive and increases with p_T
- **Sample-1**
 - In low p_T
 - Both gg and $qg < 0$
 - Slight negative A_{LL} in $\eta < 0.38$
 - In large p_T
 - Both gg and $qg > 0$
 - A_{LL} becomes large positive
- **Sample-2**
 - $gg > 0, qg < 0, A_{LL} < 0$ in whole p_T
 - $|A_{LL}|$ becomes larger to negative



Difficult to obtain sizable asymmetry in low p_T ,
since partonic cross section itself is too small.

III. Charged Pion Asymmetry



qg process dominates in large p_T

$$\Delta g \left\{ (\Delta u + \Delta d) D_g^{\pi^+} + \Delta u \cdot D_u^{\pi^+} + \Delta d \cdot D_d^{\pi^+} \right\}$$

positive

negative

$$\Delta g \left\{ (\Delta u + \Delta d) D_g^{\pi^-} + \Delta u \cdot D_u^{\pi^-} + \Delta d \cdot D_d^{\pi^-} \right\}$$

cf. $D_g^{\pi^+} = D_g^{\pi^-}$, $D_u^{\pi^+} > D_u^{\pi^-}$, $D_d^{\pi^+} < D_d^{\pi^-}$

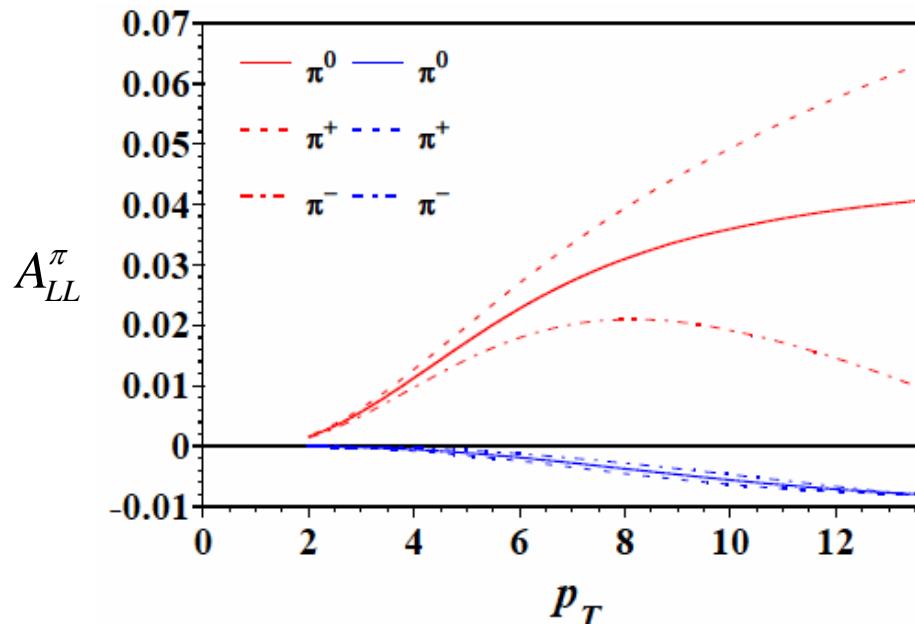
$$D_a^{\pi^0} = \left(D_a^{\pi^+} + D_a^{\pi^-} \right) / 2$$



π^+ is more promising than π^- .

Neutral π^0 vs. Charged $\pi^+\pi^-$

$$A_{LL}^\pi \approx \frac{\Delta g}{g} \cdot \frac{(\Delta u + \Delta d) D_g^\pi + \Delta u \cdot D_u^\pi + \Delta d \cdot D_d^\pi}{(u + d) D_g^\pi + u \cdot D_u^\pi + d \cdot D_d^\pi} \quad \text{in large } p_T$$



AAC $\Delta g(x)$

- Difference $p_T > 6$ GeV

$$A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$$

Sample-2 $\Delta g(x)$

(small negative $\Delta g(x)$)

$$A_{LL}^{\pi^+} \approx A_{LL}^{\pi^0} \approx A_{LL}^{\pi^-}$$

If $|\Delta g(x)|$ is small, asymmetry has no significance among π^0, π^+, π^- .

Spin Asymmetry of $\pi^+ - \pi^-$

- **Spin asymmetry**

$$A_{LL}^{\pi^+ - \pi^-} \equiv \frac{\Delta\sigma^{\pi^+} - \Delta\sigma^{\pi^-}}{\sigma^{\pi^+} - \sigma^{\pi^-}},$$

Only qg process survives!!

$$\propto \frac{\Delta g(x_a) \otimes [\Delta u_v(x_b) - \Delta d_v(x_b)] \otimes (D_1^\pi - D_2^\pi) + (a \leftrightarrow b)}{g(x_a) \otimes [u_v(x_b) - d_v(x_b)] \otimes (D_1^\pi - D_2^\pi) + (a \leftrightarrow b)}, \quad \begin{cases} D_1^\pi = D_u^{\pi^+} = D_{\bar{u}}^{\pi^-} = D_d^{\pi^-} = D_{\bar{d}}^{\pi^+} \\ D_2^\pi = D_u^{\pi^-} = D_{\bar{u}}^{\pi^+} = D_d^{\pi^+} = D_{\bar{d}}^{\pi^-} \end{cases}$$

M. Hirai and KS, PRD71,014022 (2004)

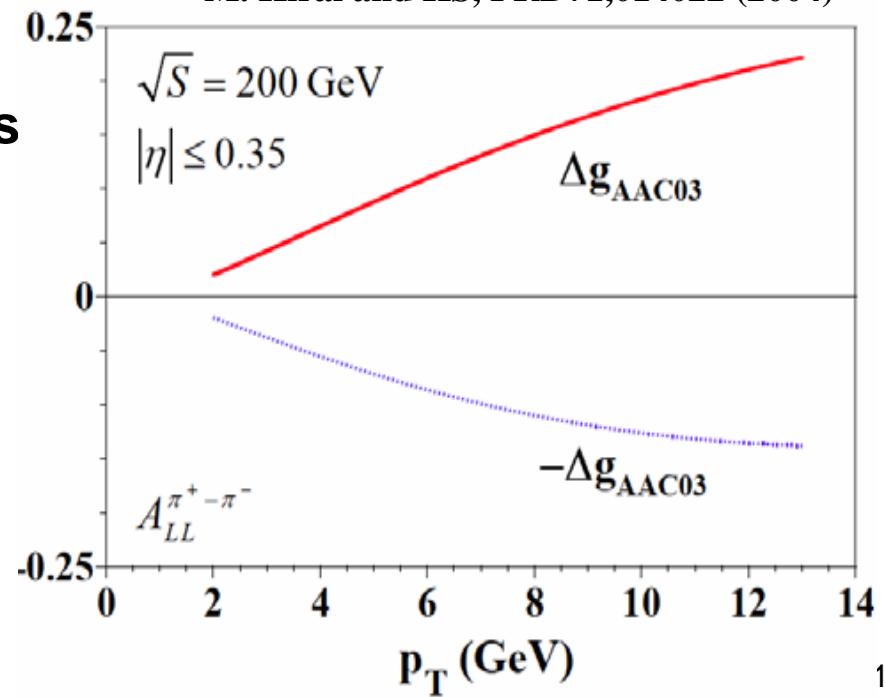
- **Advantages**

- **Elimination of other processes**

$$gg \rightarrow gg, q\bar{q} \rightarrow gg: D_g^{\pi^+} = D_g^{\pi^-}$$

$$gg \rightarrow q\bar{q}, q\bar{q} \rightarrow q'\bar{q}': \sum D_i^{\pi^+} = \sum D_i^{\pi^-}$$

- **Sensitive to the sign of Δg**
- **No $D_g^{\pi^\pm}$ ambiguity**
- **Well determined $\Delta u_v - \Delta d_v$**



Sensitivity to experimental data

p_T (GeV)	9	10	11	12	13
α	0.82	0.80	0.78	0.76	0.74
R_{sta}	7.2	6.4	5.7	5.2	4.7
R_{asym}	5.0	5.1	5.3	5.5	5.6

- Statistical errors

$$\delta A_{LL}^{\pi^+ - \pi^-} = \frac{1}{P^2} \frac{1}{\sqrt{N^{\pi^+}}} \frac{\sqrt{1+\alpha}}{(1-\alpha)}, \quad \left(\alpha = \frac{N^{\pi^-}}{N^{\pi^+}}, \quad N^{\pi^+} = L_{int} \sigma^{\pi^+} \right)$$

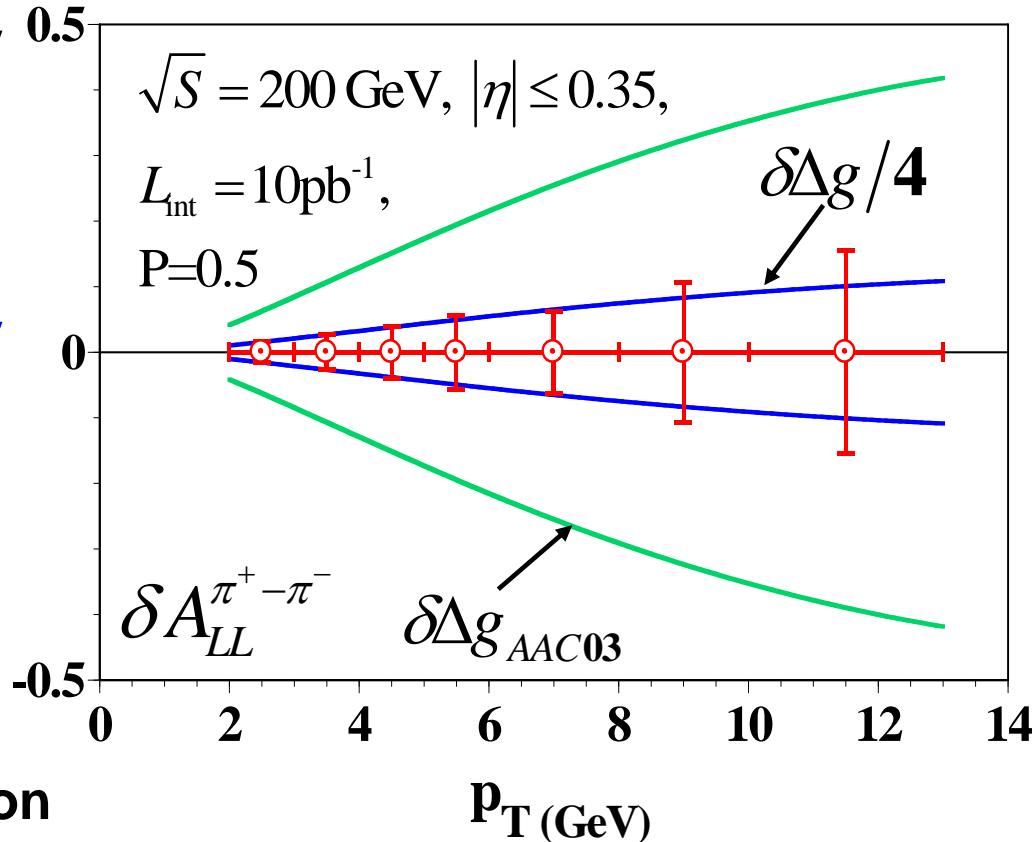
- Ratio of π^0 and π^\pm

$$R_{sta} \equiv \frac{\delta A_{LL}^{\pi^+ - \pi^-}}{\delta A_{LL}^{\pi^0}} = \frac{1}{\sqrt{2}} \frac{1+\alpha}{1-\alpha}, \quad R_{asym} \equiv \frac{A_{LL}^{\pi^+ - \pi^-}}{A_{LL}^{\pi^0}}$$

- Experimental impact: $p_T > 11$ GeV

Uncertainty of $A_{LL}^{\pi^+ - \pi^-}$

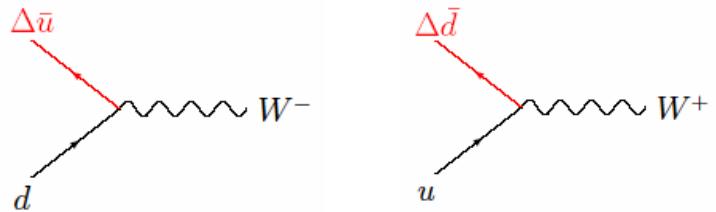
- Asymmetry uncertainty comes from Δg uncertainty
- Asymmetry uncertainty can be reduced by rather lower luminosity
 - 10 pb^{-1} : $\delta\Delta g/4$
- qg process dominates
 - Prompt photon production needs more luminosity, over 100 pb^{-1}



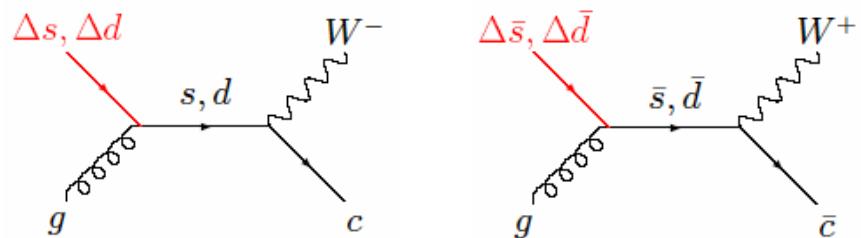
Experimental statistical error:

$$\delta A_{LL}^{\pi^+ - \pi^-} = \frac{1}{P^2} \frac{1}{\sqrt{N^{\pi^+}}} \frac{\sqrt{1+\alpha}}{(1-\alpha)}, \quad \left(\alpha = \frac{N^{\pi^-}}{N^{\pi^+}}, \quad N^{\pi^+} = L_{\text{int}} \sigma^{\pi^+} \right)$$

- 500 GeV Run
 - W^\pm Production



- Charm-Associated W^\pm Production



IV. Charm-Associated W^\pm Production

- W^\pm production is sensitive to $\Delta\bar{u}(x)$, $\Delta\bar{d}(x)$.

$$\Delta\bar{u} + d \rightarrow W^-, \quad \Delta\bar{d} + u \rightarrow W^+$$

- identified by tagging the charged lepton: $W^- l \nu$

- Charm-associated W^\pm production is also interesting!!

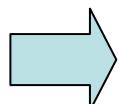
- LO $\Delta s'(\Delta g) + g(s') \rightarrow W^- + c$

- NLO $\Delta s'(\Delta g) + g(s') \rightarrow W^- + c + g$ & virtual corrections

$$\Delta g + g \rightarrow W^- + c + \bar{c}, \quad \Delta q(\Delta\bar{q}) + \bar{q}(q) \rightarrow W^- + c + \bar{s}',$$

$$\Delta s'(\Delta q) + q(s') \rightarrow W^- + c + q$$

$$s' \equiv |V_{cs}|^2 s + |V_{cd}|^2 d$$

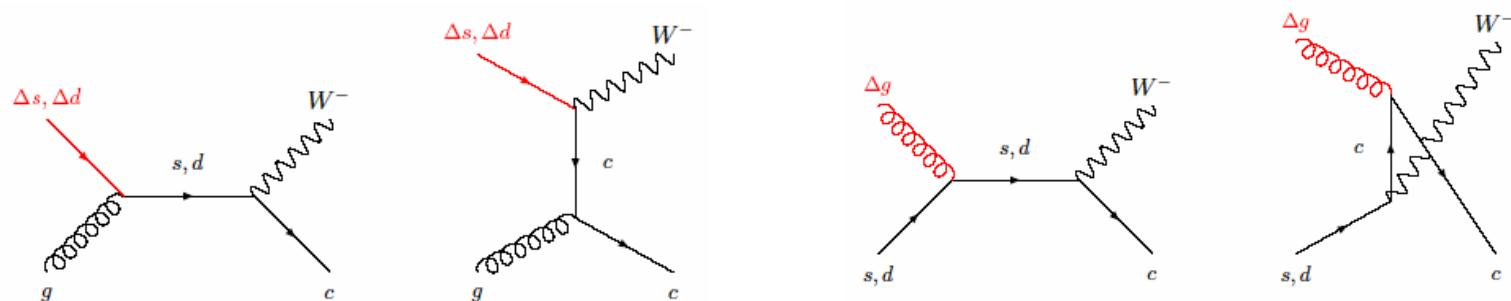


Sensitive to the polarized s quark distribution

$p + \vec{p} \rightarrow W^\pm + c/\bar{c} + X$ at RHIC

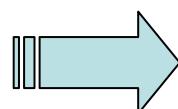
LO Diagrams of Subprocesses

- **Subprocesses for W^\pm production**
 - $O(\alpha_s \alpha_w)$ 2 2 tree-level channels in LO



well-defined in perturbation theory

- Spin asymmetry is sensitive to $\Delta s(x)$.



Need to separate $\Delta s \cdot g$ from $\Delta g \cdot s$.
Examine CKM mixing Δs and Δd .



Observables

Longitudinal Single Spin Asymmetry:

$$A_L^W \equiv \frac{[d\sigma_+ - d\sigma_-]/dp_T dy_W}{[d\sigma_+ + d\sigma_-]/dp_T dy_W} = \frac{d\Delta\sigma/dp_T dy_W}{d\sigma/dp_T dy_W}$$

$$\begin{aligned} \frac{d\Delta\sigma}{dp_T dy_W} &\equiv \frac{1}{2} \left[\frac{d\sigma_+}{dp_T dy_W} - \frac{d\sigma_-}{dp_T dy_W} \right] & : |y_W| < 1.5, \quad Q^2 = M_W^2 \\ &= \sum_{f_1, f_2} \int_{x_a^{\min}}^1 dx_a \int_{x_b^{\min}}^1 dx_b \Delta f_1(x_a, Q^2) f_2(x_b, Q^2) \frac{d\Delta\hat{\sigma}}{dp_T dy_W} \end{aligned}$$

- Polarized PDFs: $\Delta f(x, Q^2)$

- AAC

Asymmetry Analysis Collaboration,

Y. Goto, et al., *Phys. Rev.* D62, 034017 (2000).

- GRSV

M. Gl"uck, et al., *Phys. Rev.* D63, 094005 (2001).

- LSS

E. Leader, et al., *Eur. Phys. J.* C23, 479 (2002).

Polarized Cross Sections

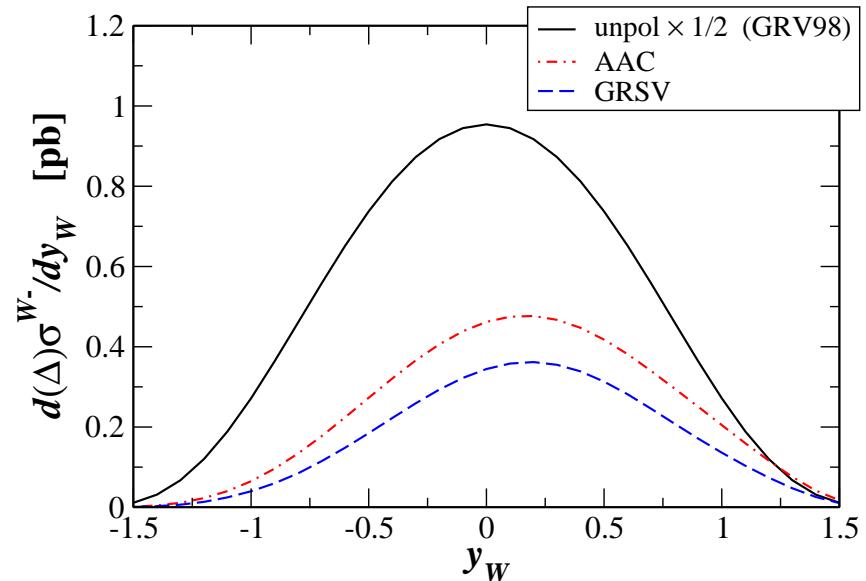
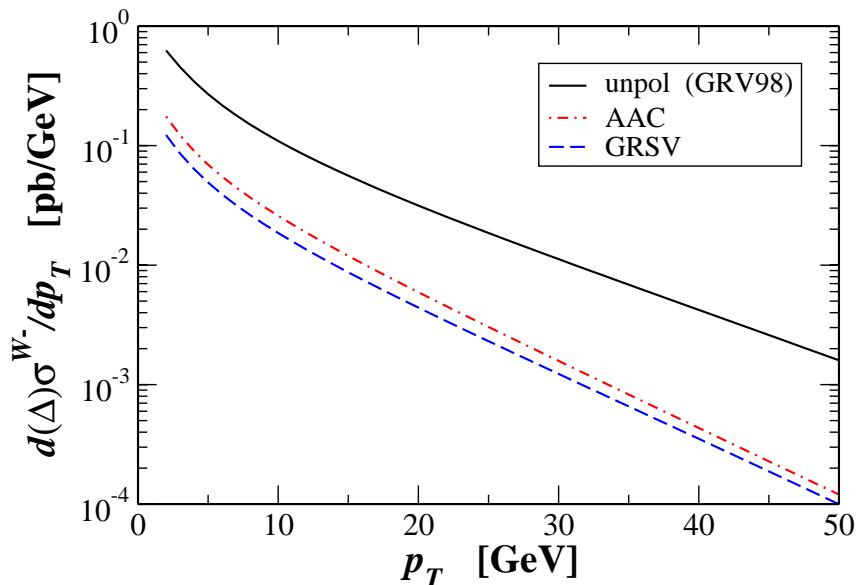
$$p + \bar{p} \rightarrow W^- + c + X$$

$$\sqrt{s} = 500 \text{ GeV}, m_c = 1.2 \text{ GeV}, Q^2 = M_W^2$$

$$\begin{aligned} \sigma &= 4.29 \text{ pb (GRV98)}, \quad \Delta\sigma = 1.105 \text{ pb (AAC)} \\ &\quad = 0.783 \text{ pb (GRSV)} \end{aligned}$$

$$\begin{cases} p_T < 50 \text{ GeV} \\ -1.5 < y_W < 1.5 \end{cases}$$

• Rapidity distribution is anti-symmetric due to the pure V-A nature of weak interaction

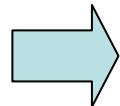


Single Spin Asymmetry

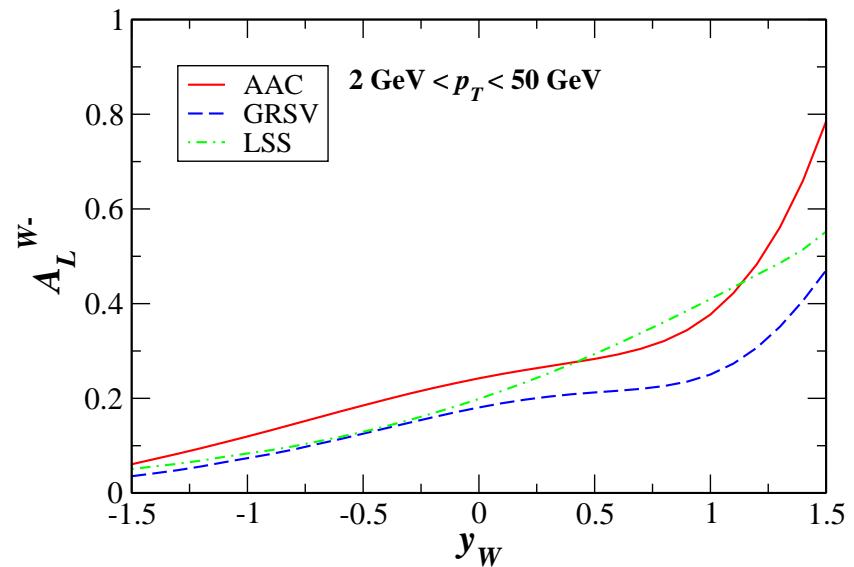
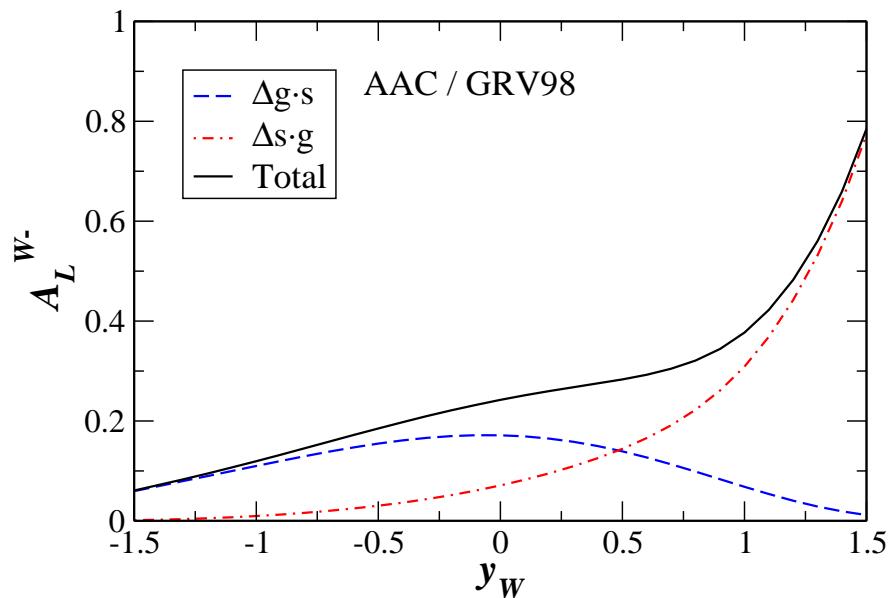
$$p + \vec{p} \rightarrow W^- + c + X$$

$$\sqrt{s} = 500 \text{ GeV}, \quad L = 800 \text{ pb}^{-1}$$

Δs dominates in $y = +1.5$, whereas Δg in $y = -1.5$.



Possibility to separate Δs from Δg



Error Estimation

- Expected Statistical Error of Asymmetry

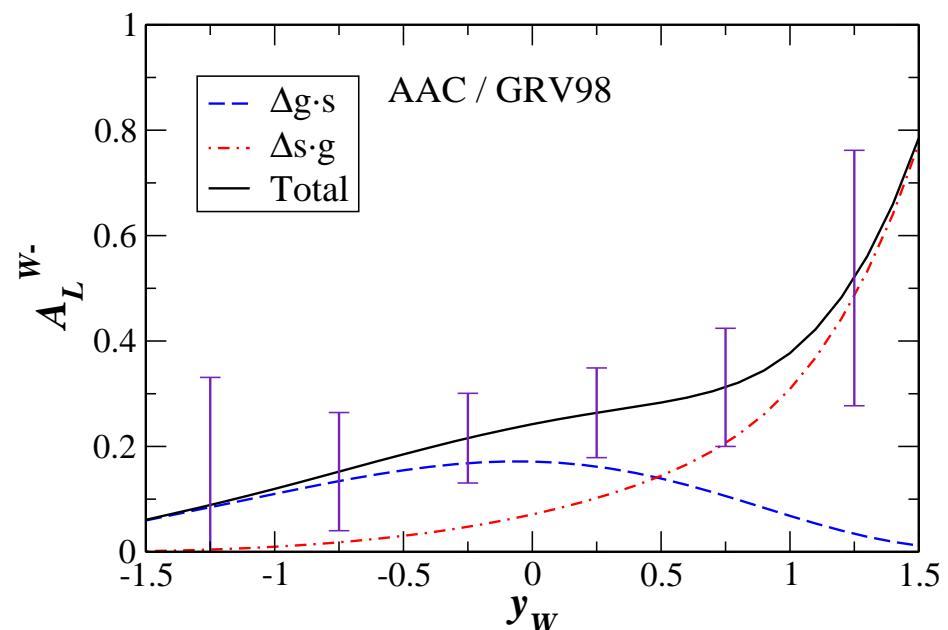
$$\delta A_L^W = \frac{1}{P} \frac{1}{\sqrt{\sigma \cdot L \cdot \varepsilon}}$$

P : beam polarization $\sim 70\%$

σ : total cross section

L : integrated luminosity $\sim 800\text{pb}^{-1}$

ε : detection efficiency $\sim 10\%$



ε might be overestimated, but the sign of $\Delta s(x)$ might be determined.

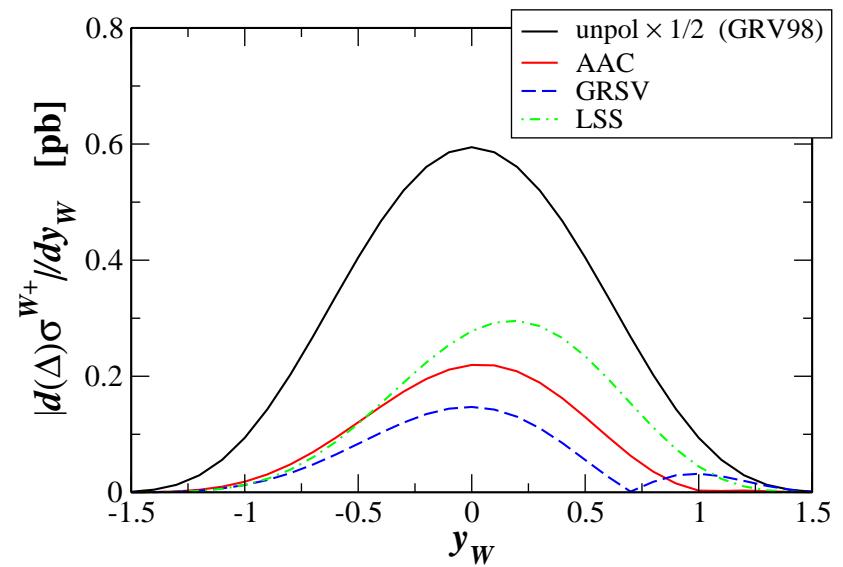
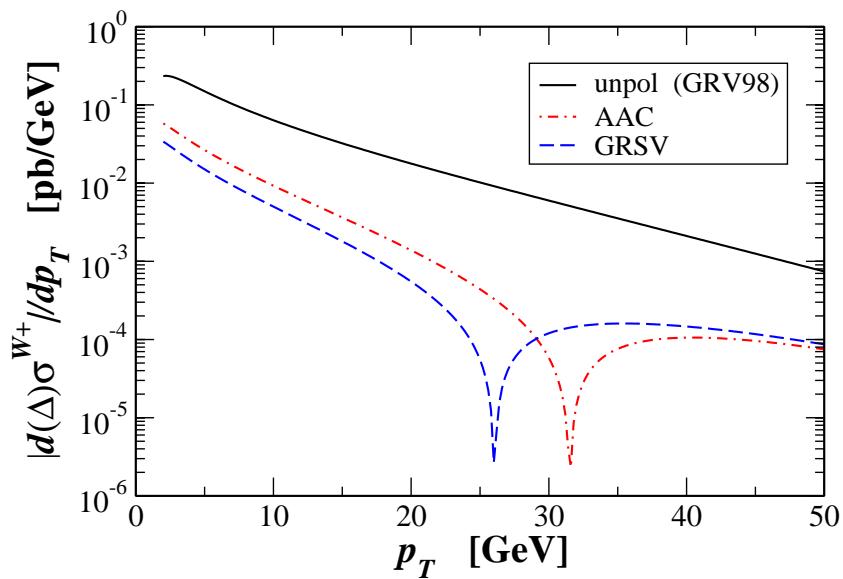
Polarized Cross Sections

$$p + \vec{p} \rightarrow W^+ + \bar{c} + X$$

$$\sqrt{s} = 500 \text{ GeV}, m_c = 1.2 \text{ GeV}, Q^2 = M_W^2$$

$$\begin{aligned} \sigma &= 1.78 \text{ pb (GRV98)}, \quad \Delta\sigma = 0.346 \text{ pb (AAC)} \\ &\quad = 0.193 \text{ pb (GRSV)} \end{aligned}$$

$$\begin{cases} p_T < 50 \text{ GeV} \\ -1.5 < y_W < 1.5 \end{cases}$$

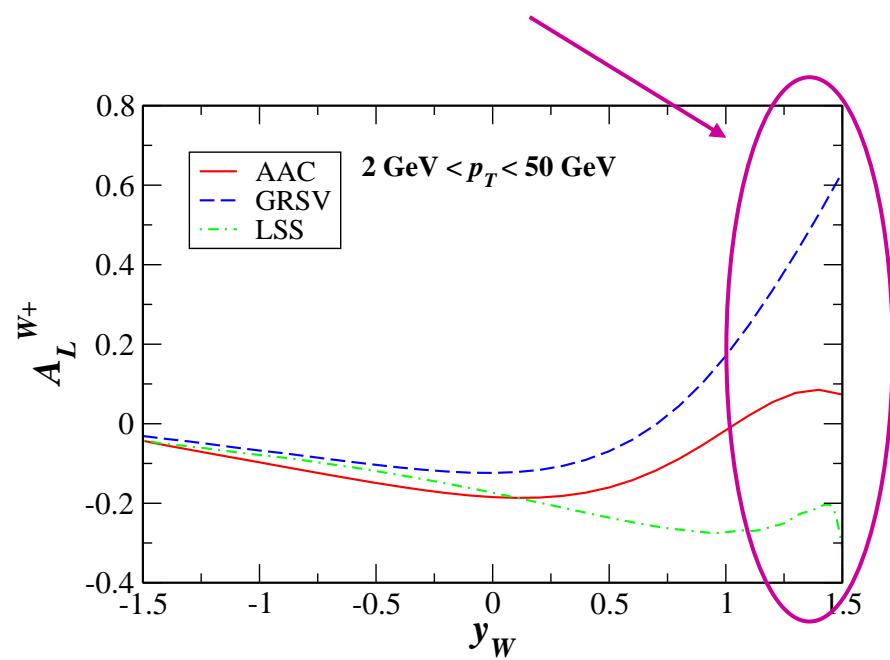
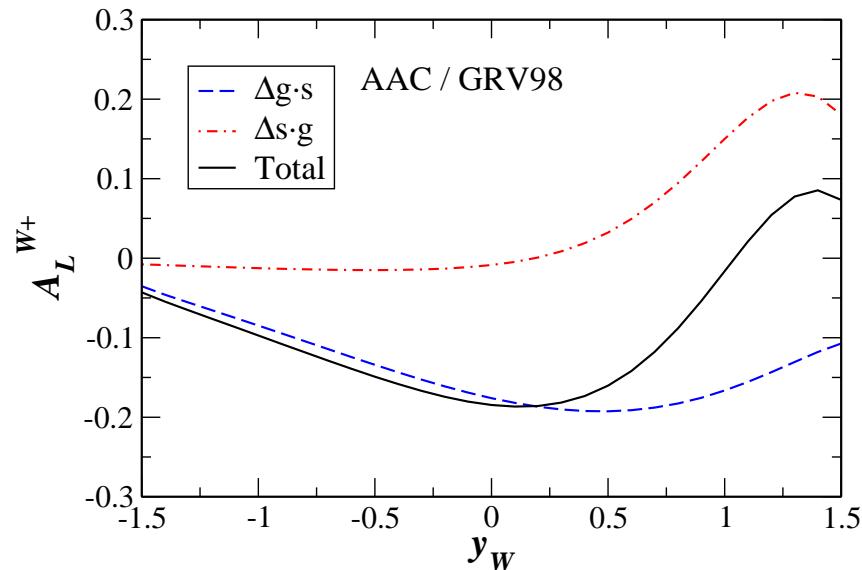


Single Spin Asymmetry

$$p + \vec{p} \rightarrow W^+ + \bar{c} + X$$

We can remove the contribution from the valence d -quark distribution. But $\Delta g(x)$ is still large in $y \sim 1.5$.

Large y behavior come form ambiguity of $\Delta s(x)$.





V. Summary

- Correlation between π^0, π^\pm spin asymmetry and $\Delta g(x)$ is studied.
 - It is extremely difficult to derive sizable A_{LL} in a few % level at low P_T , even more for negative A_{LL} .
 - Looking forward to next data.
- New asymmetry $A_{LL}^{\pi^+ - \pi^-}$ is proposed.
 - gg process can be eliminated in all order of perturbation.
 - Asymmetry is large, sensitive to the sign of Δg .
- Charm-associated W^\pm production is studied for extracting Δs .
 - It can be separated Δs from Δg .
 - Need more energy and luminosity RHIC ?